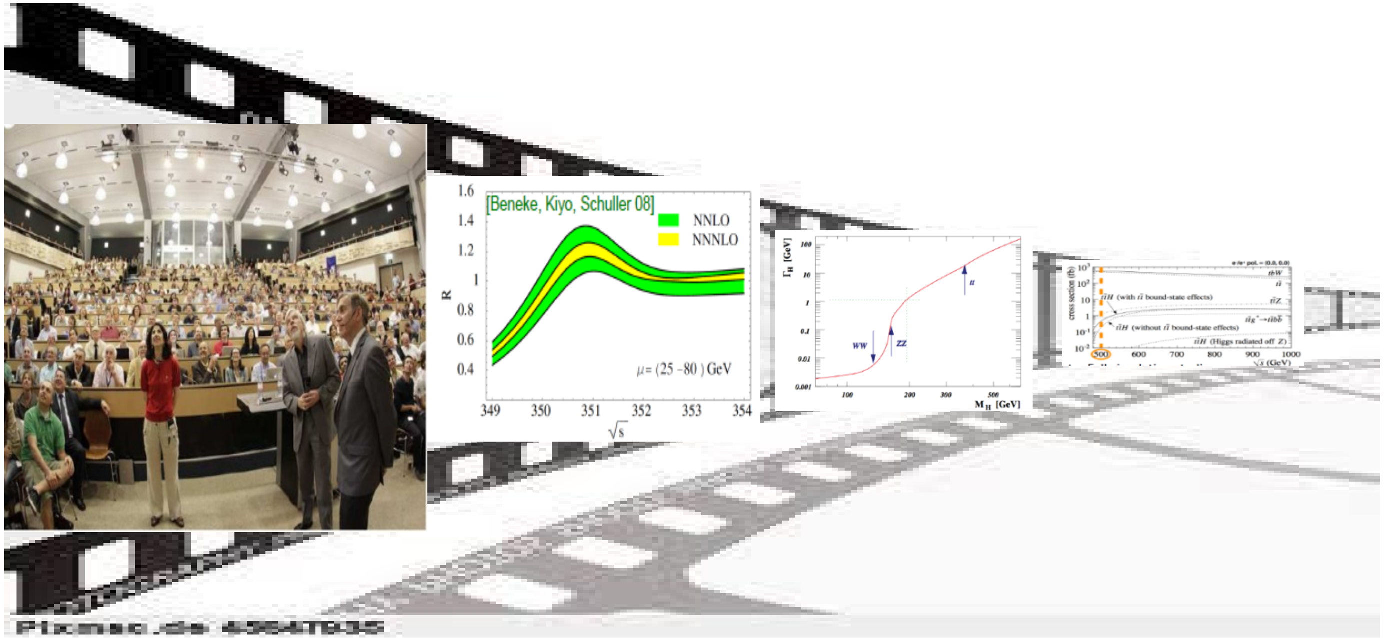
Do we need a LC to find BSM Physics?

G. Moortgat-Pick
(Uni Hamburg/DESY)



LINEAR COLLIDER COLLABORATION

Status LHC results -- in short

- Discovery of a SM-like Higgs around m_H~125 GeV
  - Is an absolute revolution!
  - Completely new type
  - Not clear whether a SM-Higgs

`The properties of the Higgs boson, to be discovered at the LHC, must be thoroughly investigated in a good condition at the ILC'
(K. Kawagoe, Feb 12)

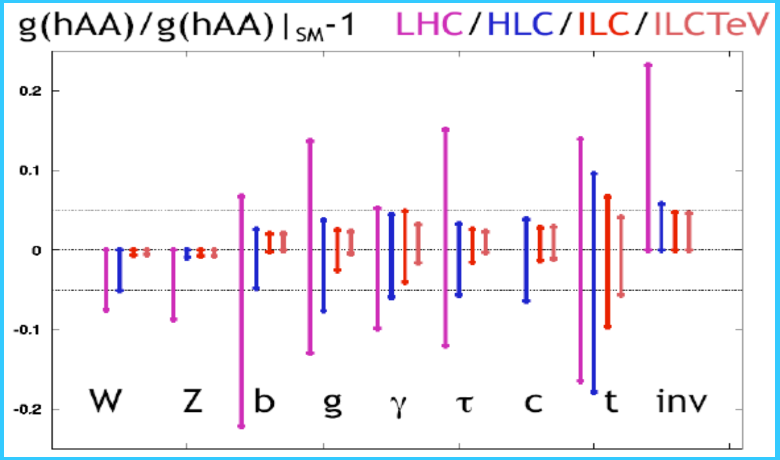
- Limits in SUSY coloured sector (approx.):
  - m_g,m_q>1 TeV
  - 3rd generation: much weaker
- Limits on Z', W': ~2 TeV
- And more limits on ED, exotics, 4th generation etc.

Physics left for a Linear Collider? Which energy steps?

Status LC -- in short

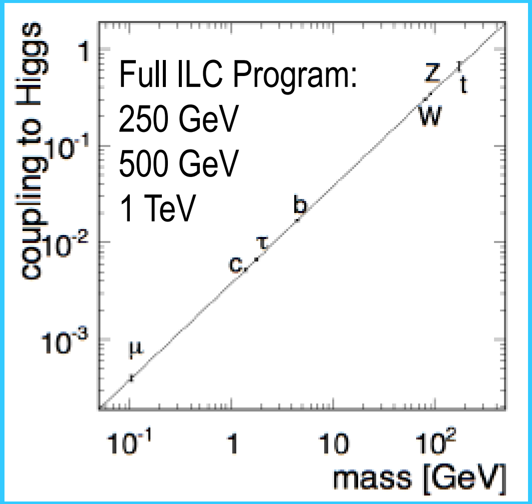
Physics

As e.g. Δm_{top}~0.1 GeV, coup$_{tth}$~5%
H: BR's~ 1 (b)-7(c)% ,Γ_h~3%, $\Delta\lambda$~18%,
CP, mixed states



Details and more examples in the many new LC reports:

- *CLIC CDR finished*
- *ILC TDR: June 12*
- *General LC review report*



This talk personal choice of

- *just new results in tricky scenarios*
- *only BSM/SUSY*

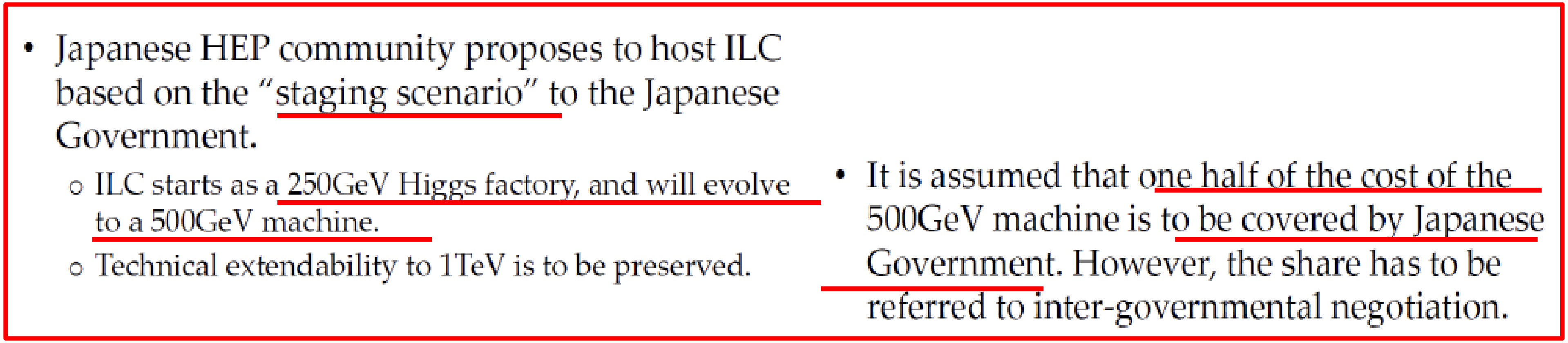
Status LC -- in short

Politics

- **ILC newsline, 7.2.13:**

On Friday, 18 January, Hakubun Shimomura, Japan’s Minister of MEXT (Ministry of Education, Culture, Sports, Science and Technology), the funding agency for Japan’s high-energy physics programme, stated Japan’s intention to invite the ILC […] Shimomura said […] I wish to carry forward to cooperate with countries concerned, and hopefully to invite it to Japan,” . Japanese government would start a preparation to start discussion, including the distribution of the construction cost, with countries concerned in the first half of 2013.

- **B. Foster, PECFA CERN 11/12:**



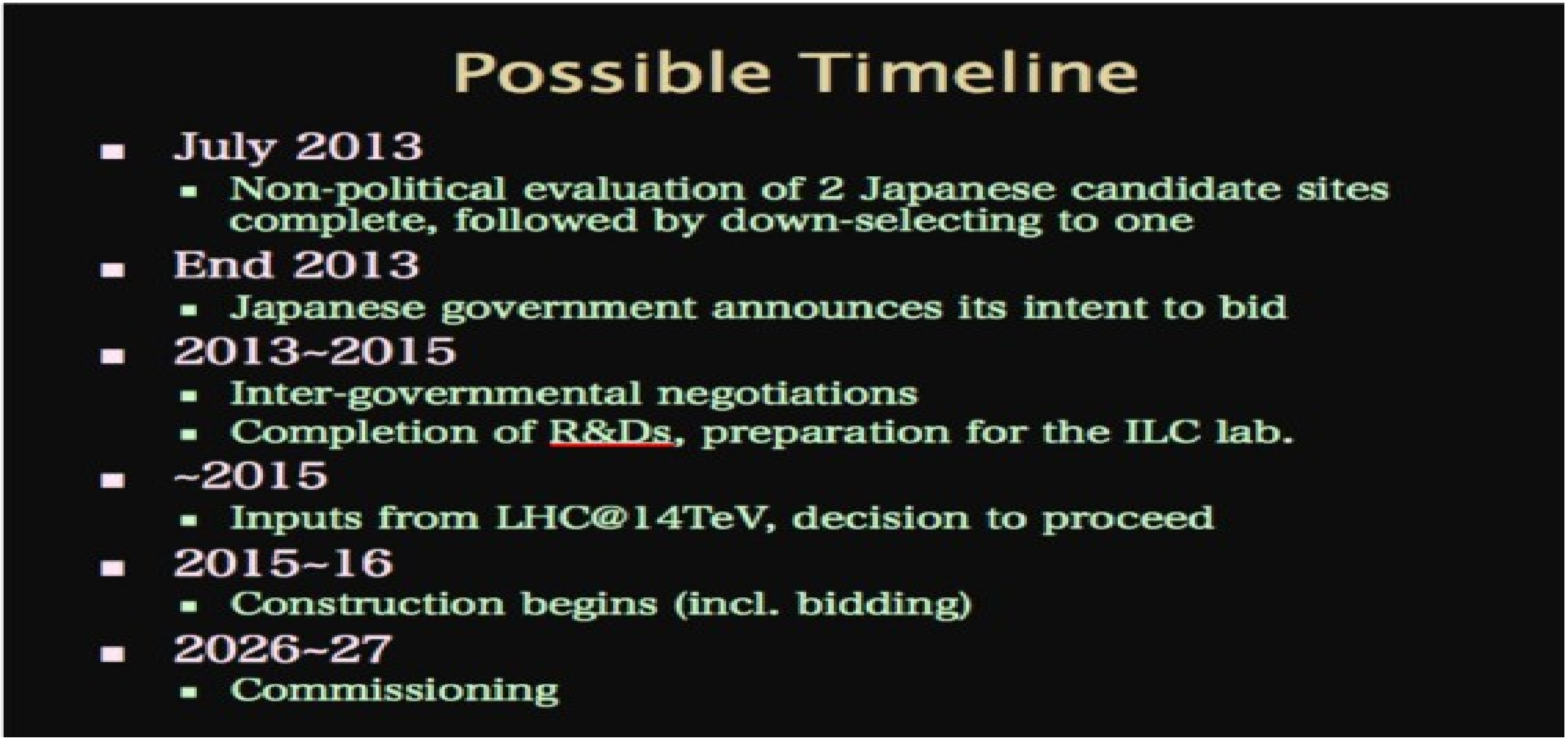
- Japanese HEP community proposes to host ILC based on the “staging scenario” to the Japanese Government.
  - ILC starts as a 250GeV Higgs factory, and will evolve to a 500GeV machine.
  - Technical extendability to 1TeV is to be preserved.
- It is assumed that one half of the cost of the 500GeV machine is to be covered by Japanese Government. However, the share has to be referred to inter-governmental negotiation.

Looks absolutely striking ….. So back to physics!

March 27th 2013

Prime Minister
MEXT Minister
Federation of Diet Members
Head of Industry alliance
...

Politics but encouraging!

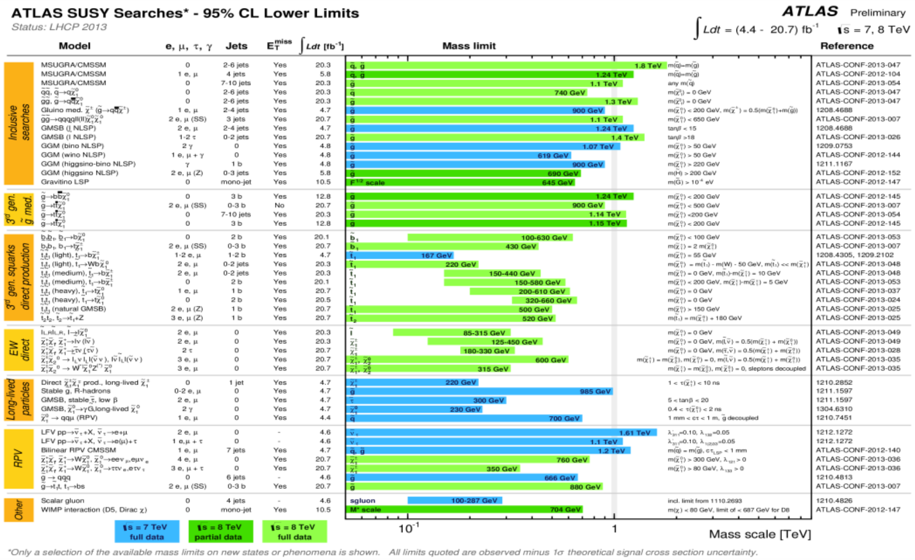


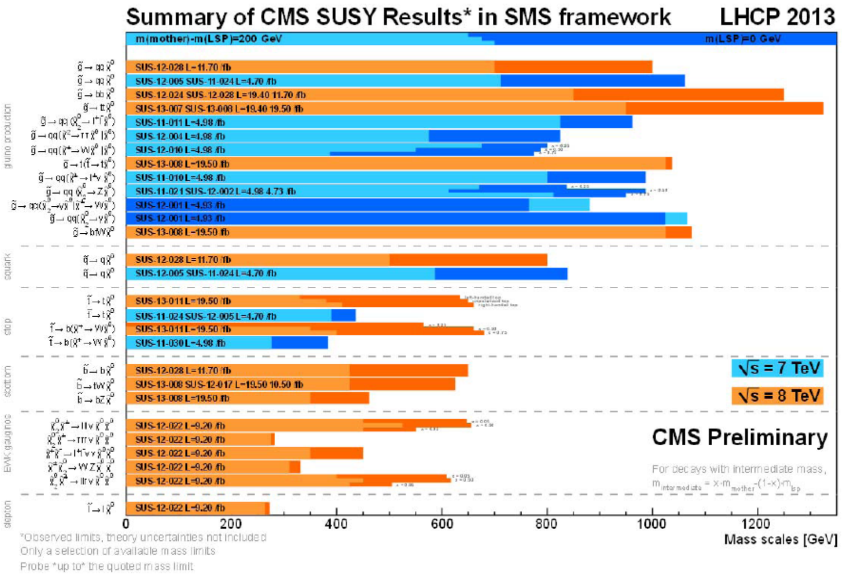
Possible Timeline

- July 2013
  - Non-political evaluation of 2 Japanese candidate sites complete, followed by down-selecting to one
- End 2013
  - Japanese government announces its intent to bid
- 2013~2015
  - Inter-governmental negotiations
  - Completion of R&Ds, preparation for the ILC lab.
- ~2015
  - Inputs from LHC@14TeV, decision to proceed
- 2015~16
  - Construction begins (incl. bidding)
- 2026~27
  - Commissioning

Impact from LHC BSM limits

- **SUSY: still strongly motivated and beautiful, but**
  - **so far, no hints of a signal, only rather high exclusion limits in the coloured sector**
  - **Constrained models (CMSSM,…) + Simpl. Models under tension!**





- **Further hints from theory?**

Further SUSY facts

- **Low energy experiments, $(g\text{-}2)_\mu$:**
  - favours rather low SUSY masses in electroweak sector:

$$\delta a_\mu(\text{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$$

    - C very model dependent, SUSY/ED ~ O(α/4π …)
  - LHC results prefer rather heavy coloured sector in 1st +2nd generation
  - Way out: rather simple
    - Decouple uncoloured and coloured sector and/or take hybrid models of SUSY breaking
    - Just leave out the constrained minimal models, that's all

Remember: Minimal SUSY contains 105 new parameter… why should nature be too simple ?

Example: New TDR benchmarks

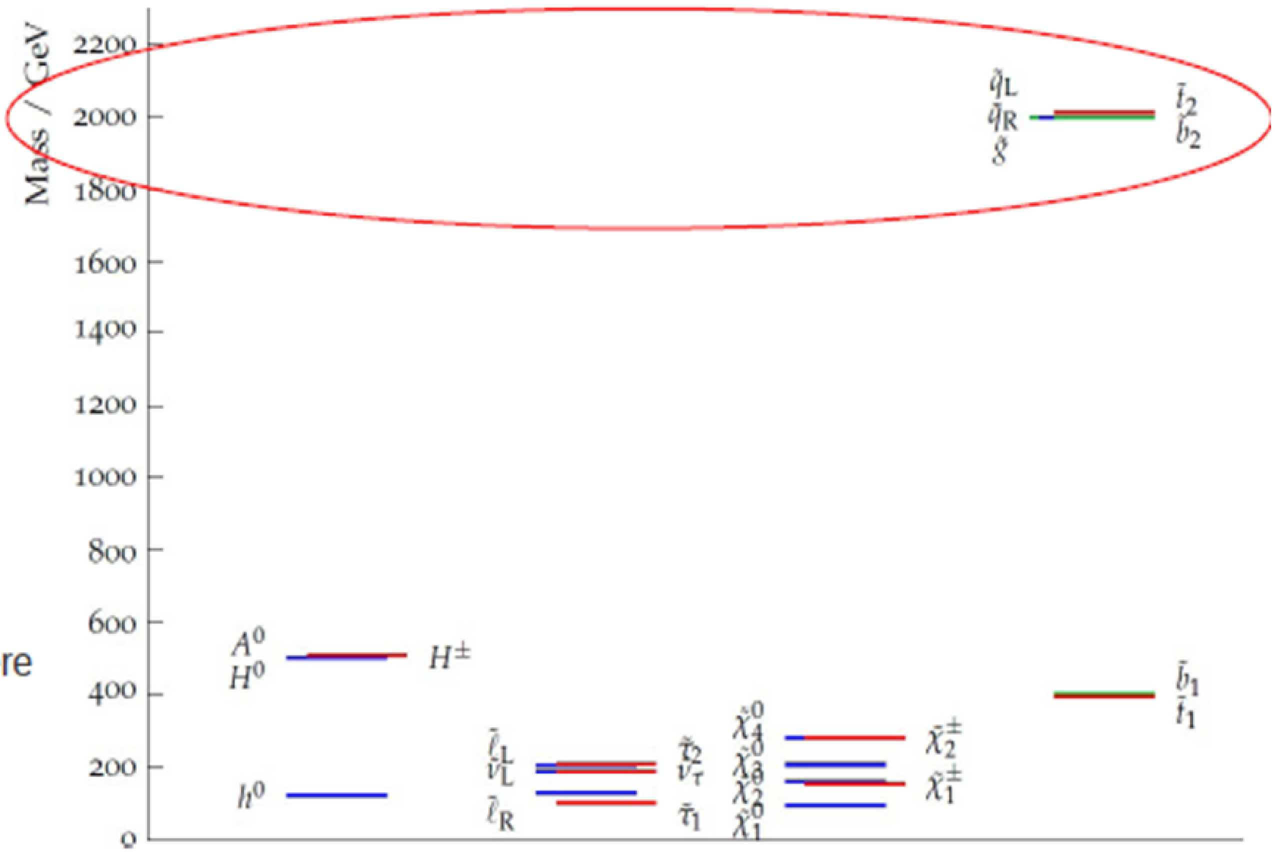
$\sqrt{s}=500$ GeV

Berggren, List, Rolbiecki '12

m_H=125 GeV:

tanβ=10
M_2=225 GeV
μ=200 GeV,…

Wonderful spectrum with rich phenomenology!



The goal of LC phenomenology: determining the structure of the underlying model and parameters!

Why 'should' light SUSY be preferred?

- **Minimization of 1-loop Higgs Potential:**

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

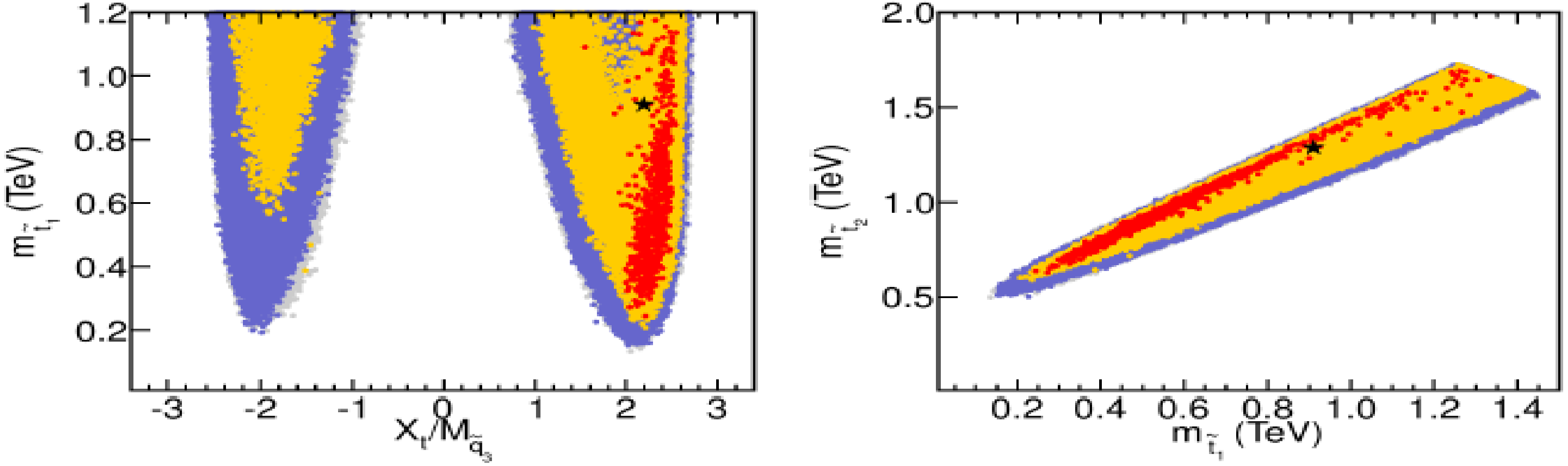
- **To keep EWFT ~ 3%:**
  - **rather small μ (~200 GeV) required**
  - **'naturalness'**
  - **Several 'natural' scenarios: light stops and light higgsinos,…**

Papucci,Ruderman,Weiler 2011
Baer,Barger,Huang, Tata, 2012

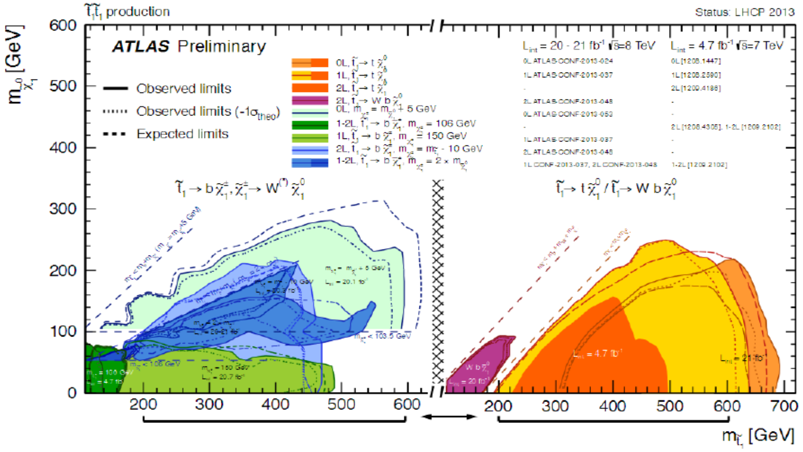
MSSM interpretation of light Higgs

- Preferred values for stop masses from fits :
- \

Bechtle, Heinemeyer,Stal,Stefaniak,Weiglein,Zeune '12



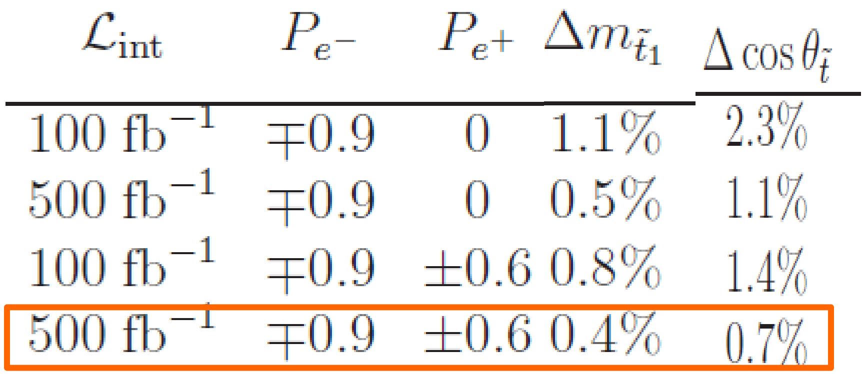
- M_h~125 GeV requires large stop mixing ~ large X_t
  - Rather large $X_t = A_t - \mu \cot \beta$
- But $m_{\tilde t}$ can still be light !



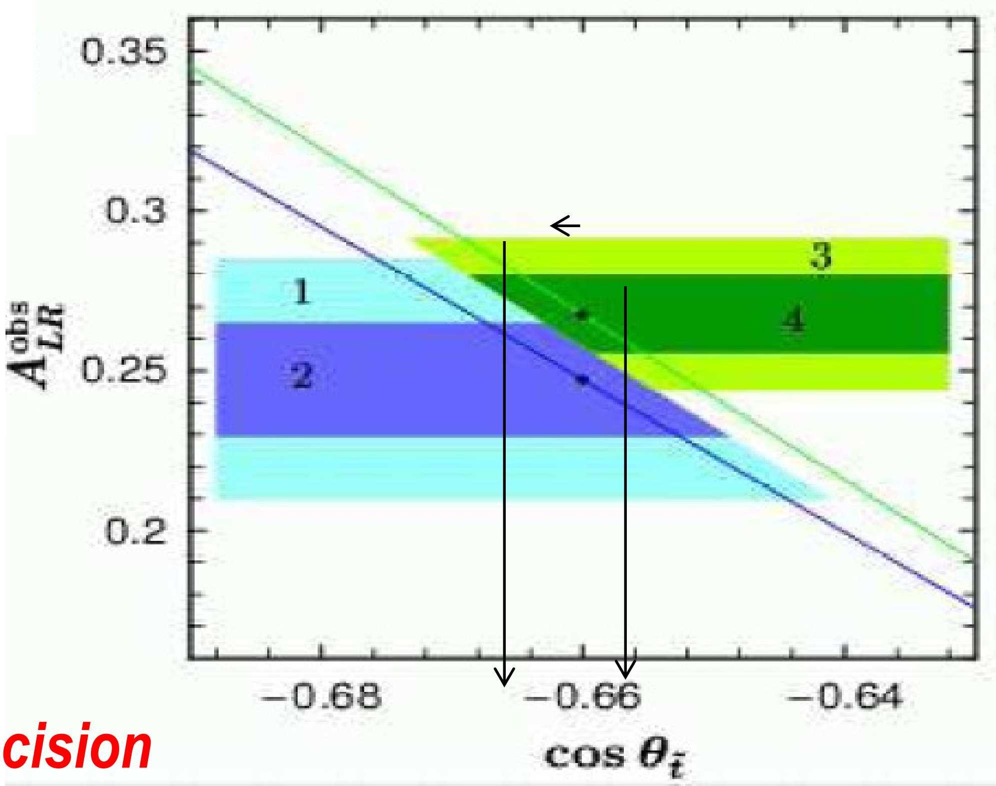
Start with stops: features at a LC

- **With polarized beams: A_{LR} applicable**

Eberl, Kraml,'05



$\mathcal{L}_{\rm int}$	P_{e^-}	P_{e^+}	$\Delta m_{\tilde{t}_1}$	$\Delta \cos\theta_{\tilde{t}}$
100 fb^{-1}	∓ 0.9	0	1.1%	2.3%
500 fb^{-1}	∓ 0.9	0	0.5%	1.1%
100 fb^{-1}	∓ 0.9	± 0.6	0.8%	1.4%
500 fb^{-1}	∓ 0.9	± 0.6	0.4%	0.7%



- **Mixing angle $\Delta\cos\theta_t < 1\%$**
  - **If $\Delta X_t \pm 1\%$: $\Delta m_h = \pm 0.2$GeV**

⟶ *matches long-term LHC precision*

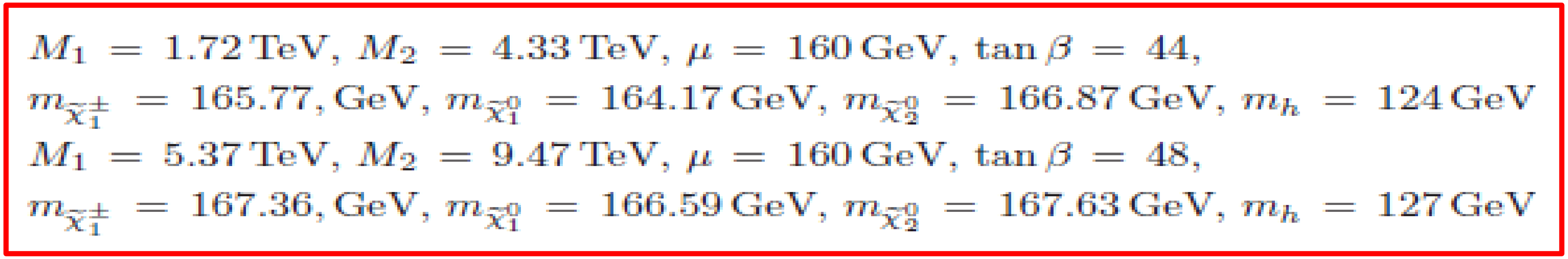
  - **If $\Delta X_t \pm 10\%$: $\Delta m_h = \pm 1.5$GeV**

⟶ *Too big to check the consistency of the model!*

Next: Higgsino-like scenarios

- **Can be embedded in hybrid gauge-gravity mediation**
  - ‘M’ driven by gauge-mediation
  - ‘μ’ driven by gravity mediation
- **Two examples as ‘prototypes’ under study**

Bruemmer,List,GMP, Rolbiecki,Sert’13



$M_1 = 1.72\,\mathrm{TeV},\ M_2 = 4.33\,\mathrm{TeV},\ \mu = 160\,\mathrm{GeV},\ \tan\beta = 44,$

$m_{\tilde{\chi}_1^\pm} = 165.77,\mathrm{GeV},\ m_{\tilde{\chi}_1^0} = 164.17\,\mathrm{GeV},\ m_{\tilde{\chi}_2^0} = 166.87\,\mathrm{GeV},\ m_h = 124\,\mathrm{GeV}$

$M_1 = 5.37\,\mathrm{TeV},\ M_2 = 9.47\,\mathrm{TeV},\ \mu = 160\,\mathrm{GeV},\ \tan\beta = 48,$

$m_{\tilde{\chi}_1^\pm} = 167.36,\mathrm{GeV},\ m_{\tilde{\chi}_1^0} = 166.59\,\mathrm{GeV},\ m_{\tilde{\chi}_2^0} = 167.63\,\mathrm{GeV},\ m_h = 127\,\mathrm{GeV}$

- **Higgsino masses:** $m_{\chi 0_1}$ ~165 GeV,$m_{\chi 0_2}$~167 GeV,$m_{\chi\pm_1}$~166 GeV
- **Feature:** Δm($_{\chi\pm1\text{-}\chi01}$)~770 MeV (1.6 GeV), Δm($_{\chi02\text{-}\chi01}$)~1.07 (2.7) GeV
  - Challenges: mass degeneration, many π’s, soft γ, E_{miss} from decay
  - How to resolve such scenarios?

Apply ISR method

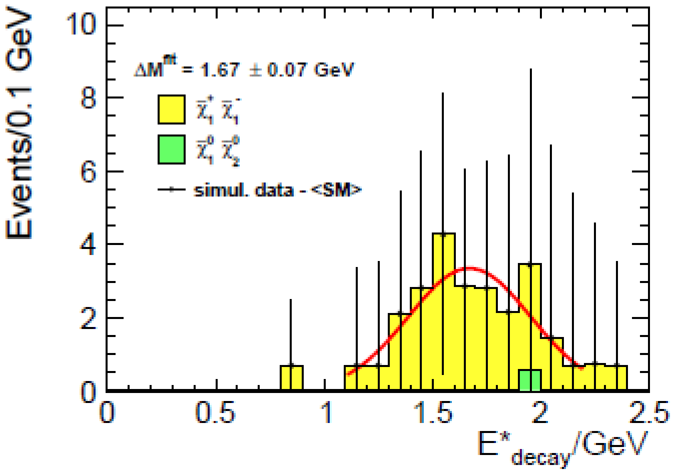
- **Accessible processes:** e+e- → $\chi^0_1\chi^0_2$, $\chi^+_1\chi^-_1$
  - Decays: χ^-_1 mainly hadronic, χ^0_2 mainly in γ's
- Measure masses via ISR method:
  - Take only events with hard γ from ISR
  - Get also rid of SM background two photons
- Measure process at two energies, √s=350 and 500 GeV
  - Use recoil mass and semihadronic channel

Berggren, List, Sert

→ *Determine MSSM parameters*

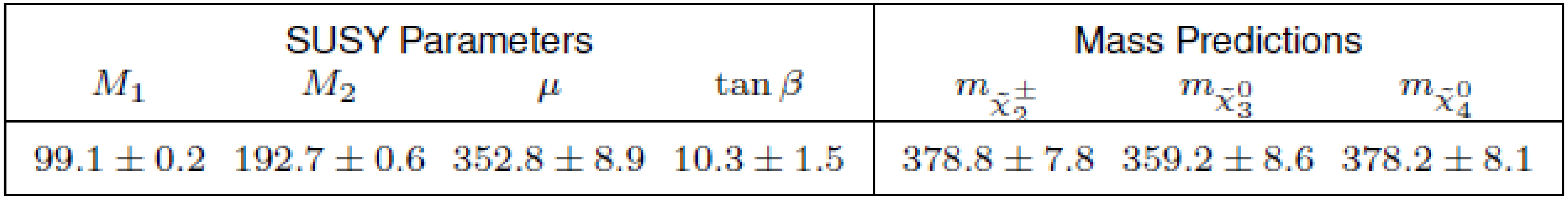
	$\sqrt{s}$ = 350&500 GeV lower	upper
M_1	1560	2050
M_2	3800	5300
μ	165.88	167.25

→



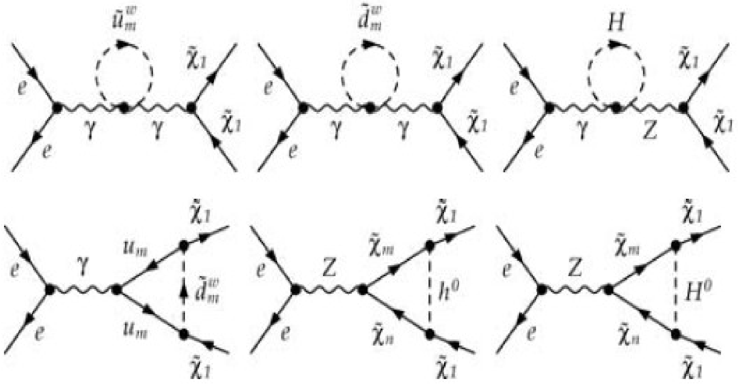
LC: Parameters from $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$@NLO

- **In the past:** parameter determination at tree level
  - Extracted from $\sigma_{L,R}$ polarized cross sections and masses $m_{\tilde{\chi}_1}$ and $m_{\tilde{\chi}^0_1}$ with 500 fb^{-1}



SUSY Parameters				Mass Predictions		
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}^\pm_2}$	$m_{\tilde{\chi}^0_3}$	$m_{\tilde{\chi}^0_4}$
99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5	378.8 ± 7.8	359.2 ± 8.6	378.2 ± 8.1

- **However:** Loop effects known to be relevant
  - Sensitivity to parameters arising from loops, e.g. stop-sector



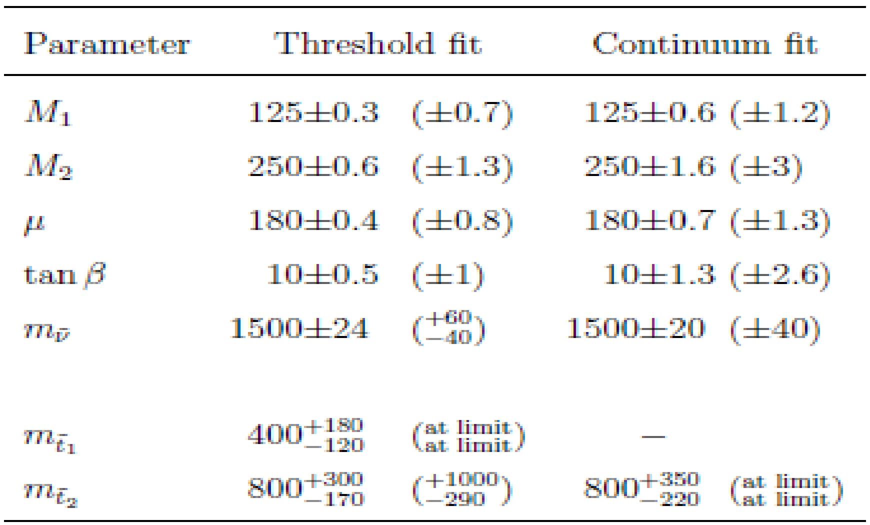
Bharucha, Kalinowski, Moortgat-Pick, Rolbiecki, Weiglein 2012

- **Now:** Strategies for parameter determination still applicable?

LC: Parameters from $e^+e^- \rightarrow \tilde{\chi}^+_1 \tilde{\chi}^-_1$@NLO

- **Strategy:** Use NLO corrected masses and $\sigma_{L,R}$ at $\sqrt{s}$=350,500
  - Use in addition A_{FB}
  - Fit of M_1, M_2, μ, $\tan\beta$ and stop sector m_{t_1}, m_{t_2} and $\cos\theta_{\tilde{t}}$
  - Compare mass accuracy from
    - Threshold scans
    - Continuum measurement

Bharucha, Kalinowski, Moortgat-Pick, Rolbiecki, Weiglein 2012



Parameter	Threshold fit	Continuum fit
M_1	125 ± 0.3 (±0.7)	125 ± 0.6 (±1.2)
M_2	250 ± 0.6 (±1.3)	250 ± 1.6 (±3)
μ	180 ± 0.4 (±0.8)	180 ± 0.7 (±1.3)
$\tan\beta$	10 ± 0.5 (±1)	10 ± 1.3 (±2.6)
$m_{\tilde{\nu}}$	1500 ± 24 $\binom{+60}{-40}$	1500 ± 20 (±40)
$m_{\tilde{t}_1}$	400^{+180}_{-120} $\binom{\text{at limit}}{\text{at limit}}$	—
$m_{\tilde{t}_2}$	800^{+300}_{-170} $\binom{+1000}{-290}$	800^{+350}_{-220} $\binom{\text{at limit}}{\text{at limit}}$

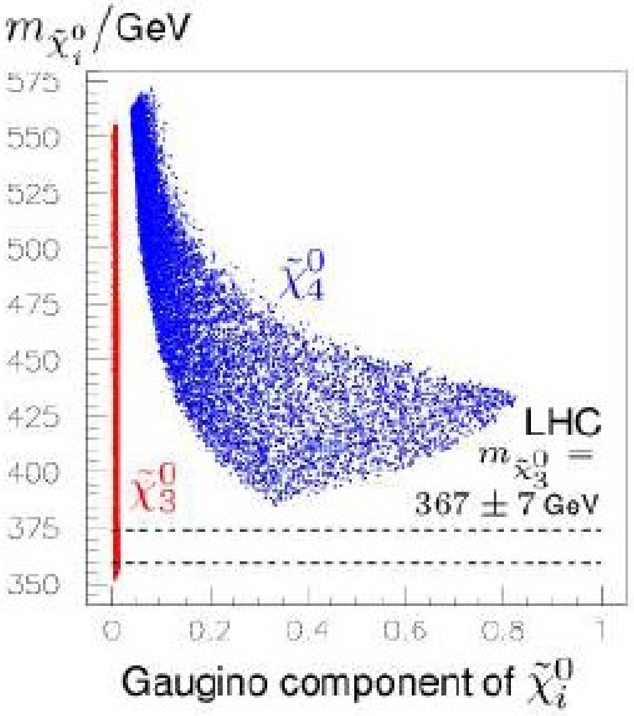
→ Relevance of threshold scans and sensitivity to heavy masses

- **Impact also on dark matter prediction:**
  - Precision needed for accurate DM prediction: accuracy of the NLO corrected parameters → 5% uncertainty in DM prediction

Challenge: MSSM vs NMSSM at LHC+LC?

- **NMSSM: Higgs singlet allows more freedom …**
  - ***Choose tricky scenario with mh~125 GeV***
    but singlet as 2nd lightest Higgs and
    M_1~360GeV, M_2~138 GeV,
    μ~460 GeV, tanβ~10,x~915 GeV
  - **similar rates and masses**
  - **pretty 'MSSM-like' phenomenology**
- **How to distinguish the model?**
  - **First hints maybe from BR($\chi^0_2 \rightarrow S\chi^0_1$)**
  - **Exploit gaugino sector:**
    parameter determination, prediction
    of heavier states
  - ***Model inconsistency clarifies the model !***

Hesselbach Franke Fraas, GMP '05,
Levermann, List, Hartin,Porto, GMP '13



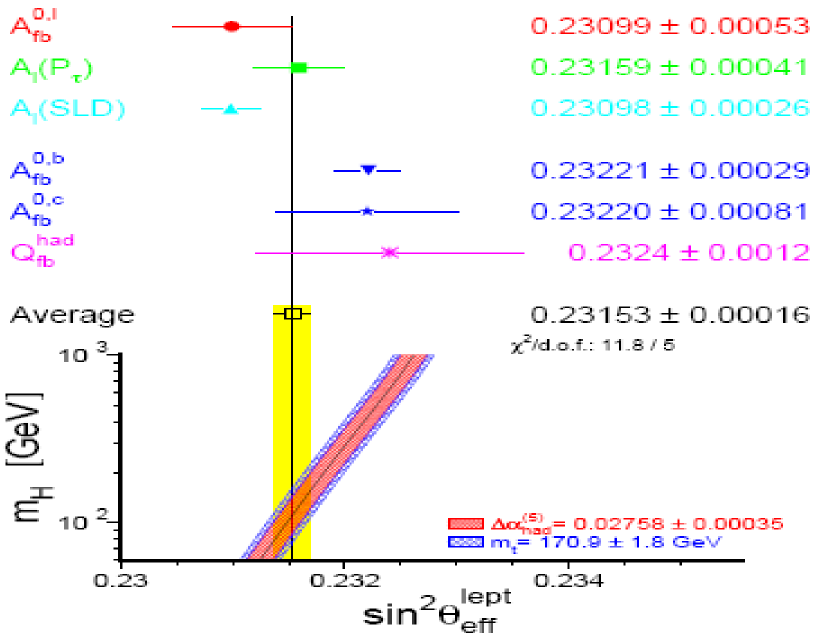
What if nothing else than H is found now?

But the exciting Higgs story has just started….

- Since m_H is free parameter in SM at tree level
  - Crucial relations exist, however, between m_{top}, m_W and $\sin^2\theta_{eff}$
  - If nothing else appears in the electroweak sector, these relations have to be urgently checked in order to
    a) distinguish between SM and Higgs in BSM models (remember $\Delta m_H \sim m^4_{top}$ in BSM!)
    b) Close the SM picture ?
- Which strategy should one aim?
  - exploit precision observables and check whether the measured values fit together at quantum level
  - m_Z ,m_W,α_{had}, $\sin^2\theta_{eff}$ und m_{top}
- Exploit \`GigaZ' option: high lumi run at $\sqrt{s}$ = 91 GeV

Higgs story has just started …

$\sqrt{s}$=91 GeV



LEP:

$\sin^2\theta_{eff}(A_{FB}^b)$= 0.23221±0.00029

SLC:

$\sin^2\theta_{eff}(A_{LR})$= 0.23098±0.00026

World average:

$\sin^2\theta_{eff}$ = 0.23153±0.00016

Goal GigaZ: $\Delta\sin\theta$=1.3 10^{-5}

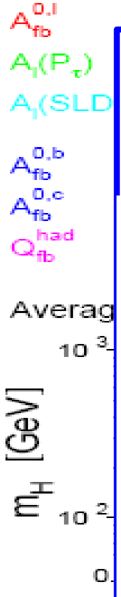
- **Uncertainties from input parameters: Δm_Z, $\Delta\alpha_{had}$, m_{top} ,...**

Heinemeyer, Kraml, Porod, Weiglein

Δm_Z=2.1 MeV:	$\Delta\sin^2\theta_{eff}^{para}$~1.4x$10^{-5}$
$\Delta\alpha_{had}$~10 (5 future) x 10^{-5} :	$\Delta\sin^2\theta_{eff}^{para}$~3.6 (1.8 future)x$10^{-5}$
Δm_{top}~1 GeV (Tevatron/LHC):	$\Delta\sin^2\theta_{eff}^{para}$~3x$10^{-5}$
Δm_{top}~0.1 GeV (ILC):	$\Delta\sin^2\theta_{eff}^{para}$~0.3x$10^{-5}$

Higgs story has just started …

$\sqrt{s}$=91 GeV



0.23099 ± 0.00053

00029

00026

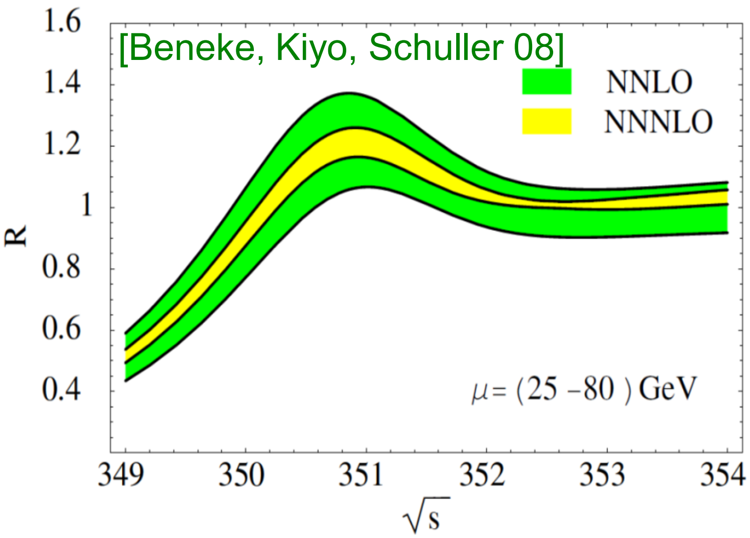
6

- Unce

Weiglein

0^{-5}

- But such a precision requires Δm_{top}=0.1 GeV



Important shift due to non-logarithmic NNNLO terms

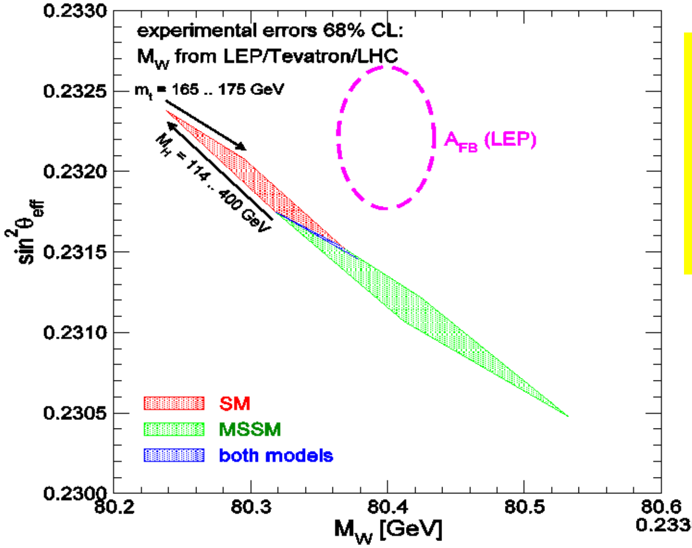
$\sqrt{s}$=350 GeV

- LC: Peak position remains stable: m_t=100 MeV expected accuracy confirmed!
- However: dedicated threshold scan required!

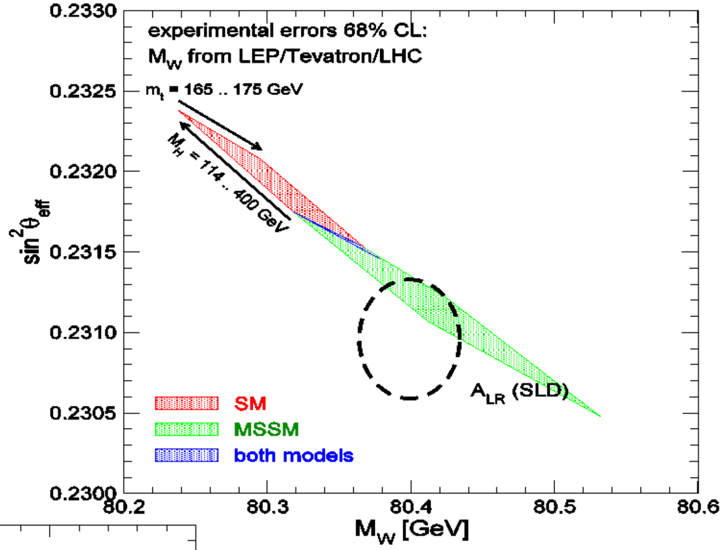
To close the story… GigaZ $\sqrt{s}=91$ GeV

- **Measure $\sin^2\theta_{eff}$ via A_{LR} with high precision: $\Delta\sin\theta=1.3\ 10^{-5}$**

Heinemeyer, Hollik, Weber, Weiglein



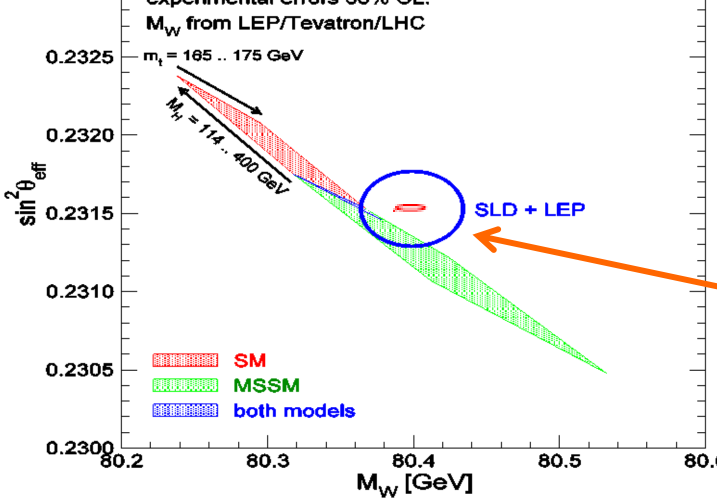
← LEP value disfavours both, SM+MSSM



↑ SLD value disfavours SM

World average → happy with both!

Central value has large impact !!!



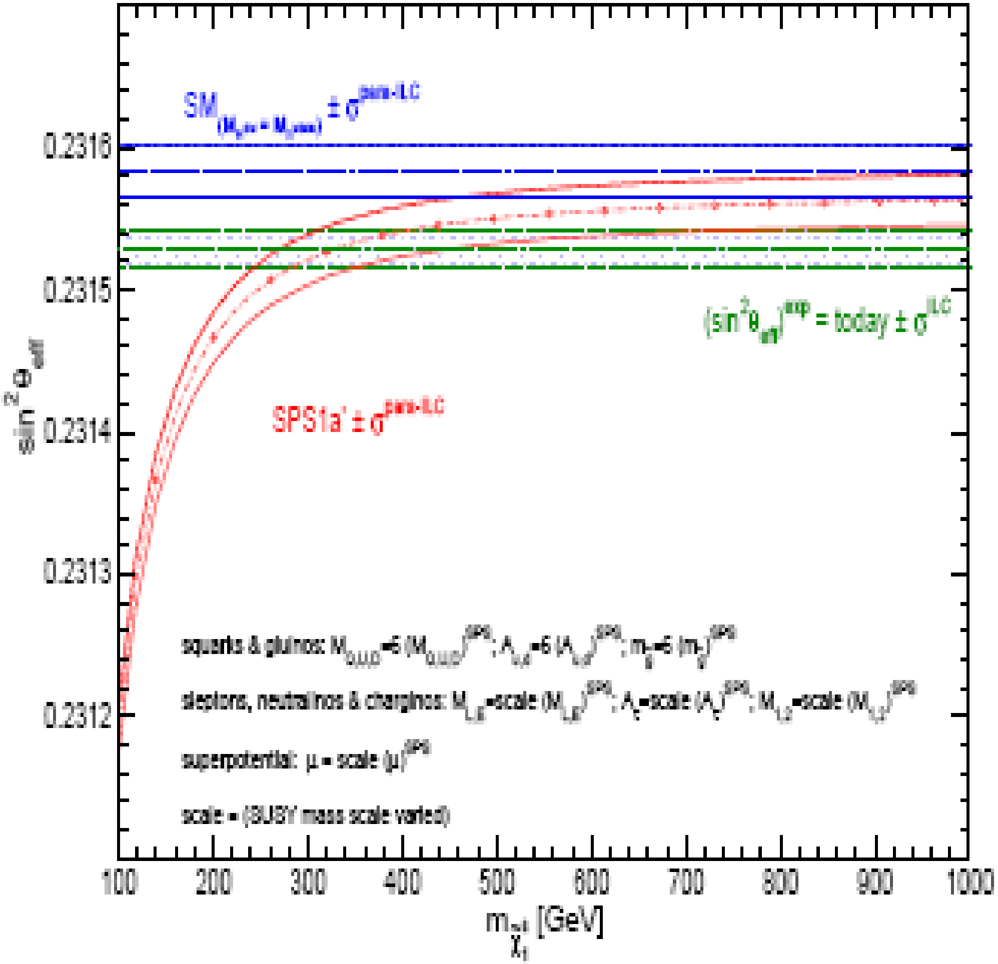
GigaZ precision!

What else could we learn?

$\sqrt{s}$=91 GeV

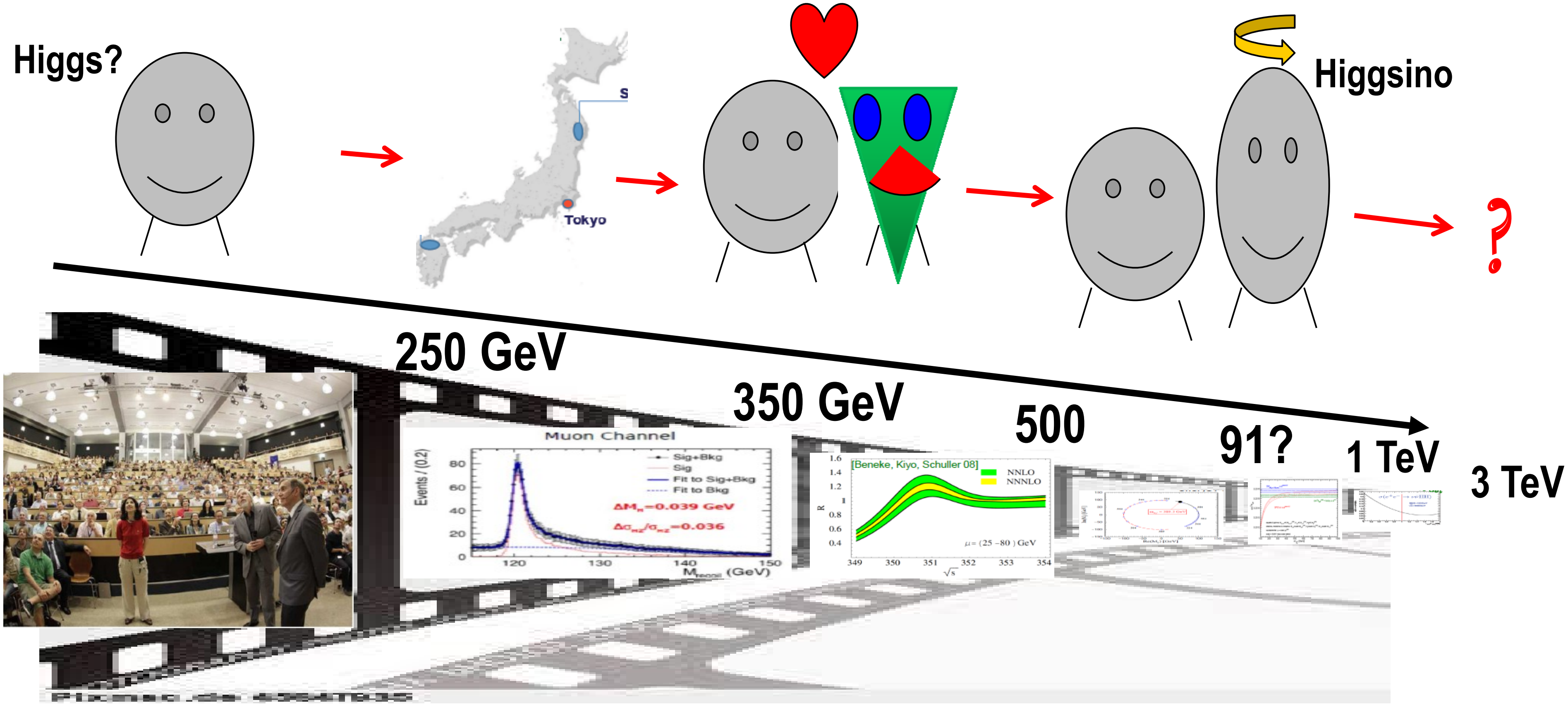
- **Assume only Higgs@LHC but no hints for SUSY:**
  - **Really SM?**
  - **Help from $\sin^2\theta_{eff}$?**
- **If GigaZ precision:**
  - **i.e. Δm_{top}=0.1 GeV…**
  - **Deviations measurable**
- **$\sin^2\theta_{eff}$ can be the crucial quantity to reveal effects of NP!**

Heinemeyer, Hollik, Weber, Weiglein



In 20 years time……we could tell a story

- Once upon a time –it was July 4th– …..



Let's do it !

Distinction of mass degenerated ew'inos

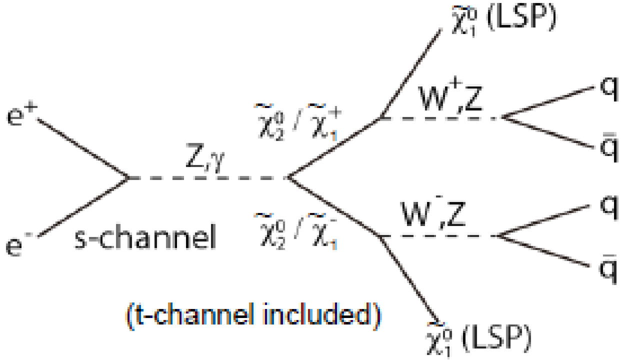
Chera, List, Suehara

- **Exploiting 'particle flow' at the LC:**

Gaugino masses:
[GeV]
(Spheno)

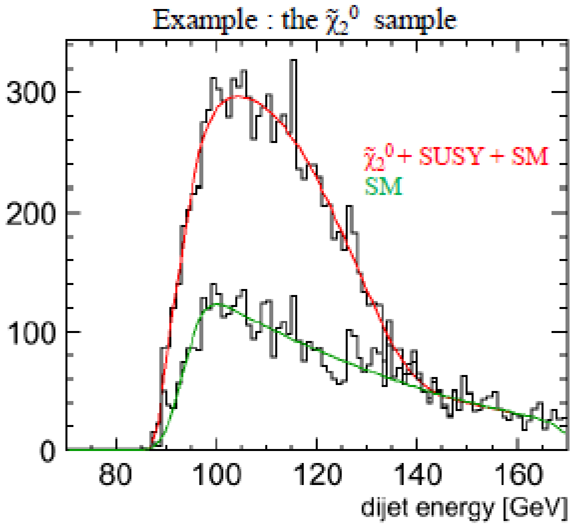
$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$
115.7	216.5	216.7	380

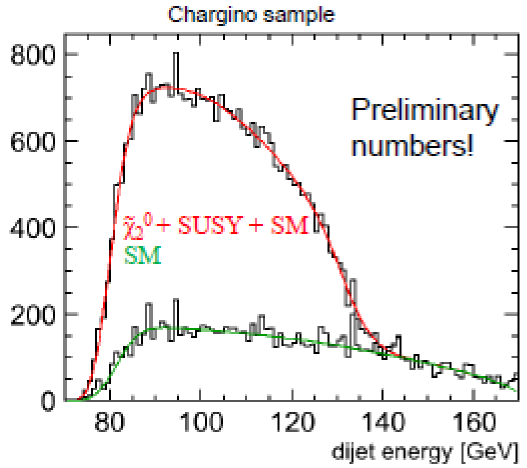
(mass degenerate)



- **Strategy (see LOI):**
  - determine M$\tilde{\chi}^\pm_1$ and M $\tilde{\chi}^0_2$ from the energy spectrum of W / Z candidates
  - separate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ based on reconstructed dijet masses:

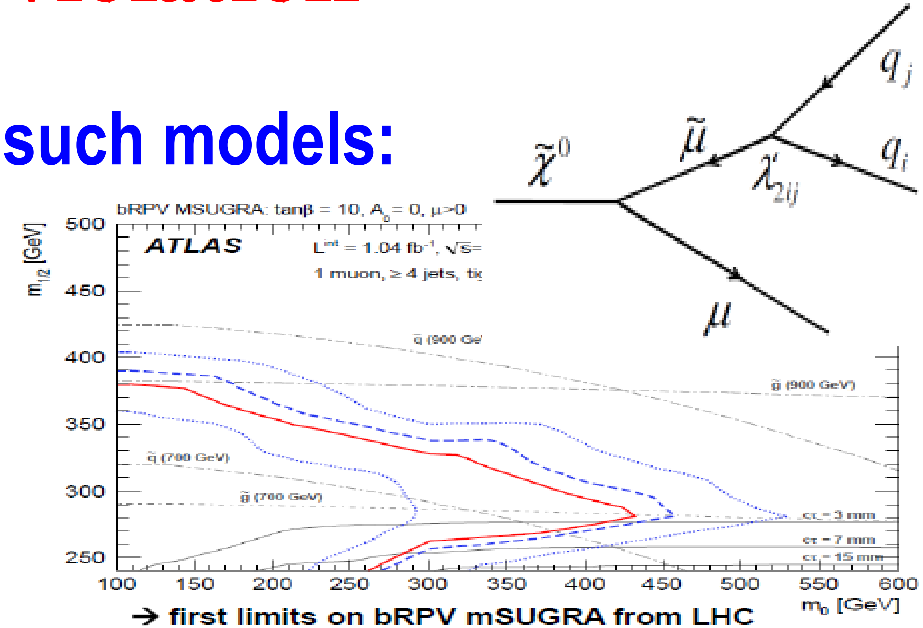
- **χ^0_2, χ^+_1 separated!**
  - **even in fully hadronic mode**





R-parity violation

- **Much lower mass bounds in such models:**



→ first limits on bRPV mSUGRA from LHC

- RPV often leads to displaced vertices
- Dedicated simulations also at LC

- **Since χ^0 and ν mix:**
  - angle θ_{23} measurable very precise at LC

Vormwald, List '12